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Phosphorus Concentrations in Overland Flow from Diverse Locations on a New York Dairy Farm

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ABSTRACT

The National Phosphorus Project rainfall simulator was used to quantify overland flow and P transport from nine sites distributed throughout the watershed of a New York City Watershed Agriculture Program collaborating dairy farm. Observed concentrations of total dissolved phosphorus (TDP) were low (0.007–0.12 mg L^{-1}) in flow from deciduous forest, extensively managed pasture, and hillside seeps; moderate (0.18–0.64 mg L^{-1}) in flow from intensively managed pastures, a hayfield, and a cow path; and extremely high (11.6 mg L^{-1}) in flow from a manured barnyard. Concentrations of TDP from sites without fresh manure were strongly correlated with soil test P (TDP [mg L^{-1}] = 0.0056 + 0.0180 × Morgan's soil test phosphorus [STP, mg kg^{-1}]; R^2 = 84%). Observed concentrations of suspended solids were low (16–137 mg L^{-1}) in flow from vegetated sites, but were higher (375–615 mg L^{-1}) in flow from sites with little ground cover (barnyard, cow path, plowed field). Under dry summer conditions the time to observed overland flow was shorter (<18 min) for nonfield areas (seeps, barnyard, cow path) than for field and forest areas (27–93 min), indicating that hydrologically active nonfield areas of minor spatial extent but with high soil P (e.g., cow paths and barnyards) can play a significant role in summertime P loading. When soils started from field capacity (second-day) time to overland flow was uniformly less than 23 min, indicating that under wet watershed conditions low-P source areas can dilute overland flow from concentrated sources.

Phosphorus loading to surface waters is an issue of environmental concern, because excess P can accelerate the growth of undesirable algae, causing eutrophication, which can lead to problems for fish, recreation, and drinking water supplies (Correll, 1998; Sharpley and Rekolainen, 1997). Whole-farm nutrient management planning (Porter et al., 1997) and the use of a field-specific P index (e.g., Gburek et al., 2000; Ketterings et al., 2001; Sharpley et al., 2001) are tools that have been developed to reduce P loading from farms. In the New York City watershed, management of agricultural P-loading source areas has been addressed through the development of best management practices designed to reduce stream water loading of nutrients and pathogens, implemented on collaborating farms using a Whole Farm Planning process (Delaware County Department of Watershed Affairs, 2002). Improved management practices are often designed to limit manure spreading on hydrologically active areas, manure deposition adjacent to or in the stream, and overland flow from manured impervious areas such as barnyards. It is important to recognize that P loading originates from diverse source areas, including agricultural soils, manured fields, and nonfield areas (e.g., barnyards and cow paths). Potential for P loss is substantial wherever hydrologic source areas overlap with areas of high P source potential (Gburek et al., 2000; Sharpley et al., 2002; Walter et al., 2000).

An improved and quantitative understanding of P loading from agricultural landscapes has emerged from recent research. For example, field studies using simulated rainfall application (Pote et al., 1996; Sharpley, 2000; Sharpley et al., 2001) have provided empirical evidence for the functional relationship between P concentrations in overland flow and soil test phosphorus (STP). On dairy farms within the New York City watershed, increased STP is associated with soils receiving long-term manure application, and STP values tend to decrease with increasing distance from the barn. While STP plays a large role in determining P concentrations in overland flow, additional factors, such as slope, ground cover, soil type, landscape position, and nutrient application are also important (Kleinman et al., 2002; Sharpley and Tunney, 2000). Recently applied manure, in particular, can produce high concentrations of TDP in overland flow, overwhelming the effect of STP (Kleinman et al., 2002; Sharpley et al., 2000). In addition, significant loads of particulate phosphorus (PP) can originate in areas prone to erosion. The concentration of total suspended solids (TSS) in overland flow is largely determined by soil texture, infiltration rate, rainfall intensity, slope, and ground cover (Renard et al., 1997), and sediment eroded from a high STP soil will contribute a greater quantity of PP per quantity of TSS (Sharpley and Smith, 1991). Although controls on P losses in overland flow from agricultural fields are now generally understood, some important challenges remain. In particular, the relative importance of P contributions from nonfield areas such as barnyards, stream crossings, and cow paths is poorly understood, especially with respect to seasonal differences in the hydrological cycle.

Ideally, an accurate simulation of P loading from the whole-farm landscape could be derived from spatially explicit characterization of fields, nonfield P-loading problem areas, and nonfield sources of low-P runoff, in the context of farm operations and in conjunction with distributed hydrological modeling of overland flow produc-

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Abbreviations: GRN, north intensively grazed pasture; GRS, south intensively grazed pasture; HAY, recently cut hayfield; HYD, heifer barnyard; PAS, extensively grazed heifer pasture; PP, particulate phosphorus; PTH heifer cow path; SHP, spring area in extensively grazed heifer pasture; SMZ, spring area in plowed maize field; STP, soil test phosphorus; TDP, total dissolved phosphorus; TSS, total suspended solids.

tion. Distributed simulation of P loading processes requires a practical means of parameterizing overland flow coefficients for various P source areas, based on empirical relationships and spatially explicit observations. The USDA-ARS National Phosphorus Project rainfall simulator has been used with success to develop soil-specific relationships between STP and concentrations of P in runoff (Sharpley et al., 1996; Sharpley, 2000). The rainfall simulator provides a consistent, standardized, in-field method that can be used to evaluate P loading to runoff from a wide variety of locations, soils, and experimental treatments (National Phosphorus Research Project, 2001; Sharpley et al., 2000). This rainfall simulator was used in the present study to measure P loading from nine diverse source areas within an intensively monitored dairy farm watershed, including extensively managed pasture, intensively managed grazing (recently grazed and regrowth), recently cut hay, hillside seeps [pasture and tilled maize (*Zea mays* L.)], a cow path, and a barnyard.

The objectives of this study were to (i) characterize P contributions from apparent P loading problem areas such as a near-stream heifer barnyard, (ii) assess the relative importance of P losses from sites throughout the watershed, and (iii) provide data to support the development of extraction coefficient parameters for distributed modeling of P loading from dairy farms within the watersheds contributing to the New York City reservoir system.

MATERIALS AND METHODS

Site Description

The study took place on a dairy-farm watershed that drains to a tributary of the West Branch of the Delaware River, above its entry point into Cannonsville Reservoir. The Cannonsville is the third largest of 19 reservoirs that provide drinking water to New York City, and often experiences eutrophication during the summer months (Effler and Bader, 1998). Since 1993 the farm has, along with a nearby nonfarm site, been the subject of a paired-watershed monitoring experiment evaluating the success of agricultural best management practices for P load reduction (Bishop et al., 2003). Improved infrastructure and improved nutrient management practices, adopted by the farm in 1995, reduced event-based loading of TDP by 49% in the summer months, and by 43% overall (Hively and Stedinger, 2003). The extensive stream quality dataset and detailed management records available for this farm provide an ideal context for whole-farm simulation of P loading processes, based on spatially explicit parameterization of P loss coefficients throughout the watershed and distributed simulation of runoff production (Gérard-Marchant et al., 2003). The 160-ha watershed encompassing the study farm is 53% forest, 13% unimproved pasture, 25% improved pasture/hay, 7% tilled crop rotation, and 2% impermeable surface. Deciduous forest dominates the upper slopes of the watershed, pasture is concentrated in the midslope areas, and intensively managed agricultural fields are located in the valley bottom (Fig. 1). The farm maintains approximately 85 milking cows and 30 replacement heifers, and produces roughly 2700 Mg of manure annually (1600 kg P), which is spread within the farm watershed according to Whole Farm Planning recommendations (Bishop et al., 2003).

The climate of the study area is humid continental, with an average temperature of 8°C. Average annual precipitation for the region is 1120 mm yr^{-1}, with approximately one-third falling as winter snow. Due to its elevation (601–735 m above sea level) the farm experiences a somewhat colder temperature regime than the lower-valley farmland nearer to the West Branch of the Delaware River. Larger stream flow volumes are generally observed in the wet winter season (November–May: 76% of annual flow from 1996–2000) than during the dry summer months, due to snowmelt and rainfall on a larger extent of saturated soils.

Well-drained soils on the upper slopes are shallow to moderately deep over horizontally bedded sandstones, siltstones, and shales (0.2–1.0 m) and include Halcott channery loams (loamy-skeletal, mixed, active, frigid Lithic Dystrudepts) and Vly channery silt loams (loamy-skeletal, mixed, superactive, frigid Typic Dystrudepts). In contrast, soils in the valley bottom are fragipan limited (0.2–0.7 m), as characterized by the moderately well-drained Willowemoc channery silt loams (coarse, loamy, mixed, frigid Typic Fragiochrepts) and the Onteora silt loams (coarse-loamy, mixed, semiactive, frigid Aquic Fragiudepts). The fragipan is thought to be somewhat more restrictive to downward water movement (1 mm d^{-1}) than bedrock (2 mm d^{-1}) due to widely spaced fractures in the bedrock.

Rain application plots were established in nine landscape positions throughout the farm watershed (Fig. 1), at sites selected to evaluate potentially different source area types for P loading. Site selection was biased toward flow-producing areas. Site codes and characteristics are listed in Table 1. Photographs of the sites are available in Hively (2004). Four sites were established within vegetated agricultural fields, and five sites were located in contrasting nonfield areas. The sites included: a swale area in an extensively managed pasture (PAS); two (north, south) rotationally grazed, intensively managed pastures (GRN, GRS); a recently cut hay field (HAY); a spring area within a plowed maize field (SMZ); a spring area within a heifer pasture (SHP); a near-stream heifer barnyard (HYD); a compacted cow path (PTH) near a stream crossing; and a frequently saturated area within an upper-slope deciduous forest catchment (FOR).

Simulated rain application took place between 25 June and 15 July 2001. Each site was sampled on two consecutive days. First-day conditions represented dry, mid-summer weather, approximately 1 wk after the first hay cut was completed. Second-day sampling represented wetter soil conditions more typical of winter-season precipitation events. Previous natural rainfall on the farm watershed included 1.3 and 16 mm falling on 23 and 24 June, and 6.4 and 3 mm falling on 11 and 13 July.

Sample Collection and Analysis

At each of the nine sampling sites, steel frames were used to define two adjacent plots (A and B), each 1 m wide by 2 m long. The frames were driven into the ground to a depth of 8 cm, and were caulked to prevent water flow around the edges. They were placed such that surface overland flow flowed into covered collection gutters at the down-slope edge of each plot. After plot frames were installed, the plot slope was measured with a transit level. Any tall vegetation within the plots was trimmed to a maximum height of 10 cm (necessary only on SHP), with clippings removed from the plot. Percent ground cover for each plot was estimated by visual inspection (Mueller-Dombois and Ellenberg, 1974, p. 80–90). The USDA-ARS National Phosphorus Project portable rainfall simulator used in this study provides a consistent, standardized, in-field method that can be used to evaluate P loading to overland flow (National Phosphorus Research Project, 2001; Sharpley et al., 2000). The device employs a single TeeJet 1/2HH-SS50WSQ nozzle (Spraying Systems, Wheaton, IL) at a 3-m height, with a nozzle pressure of 28 kPa to deliver even rainfall with a median volumet-

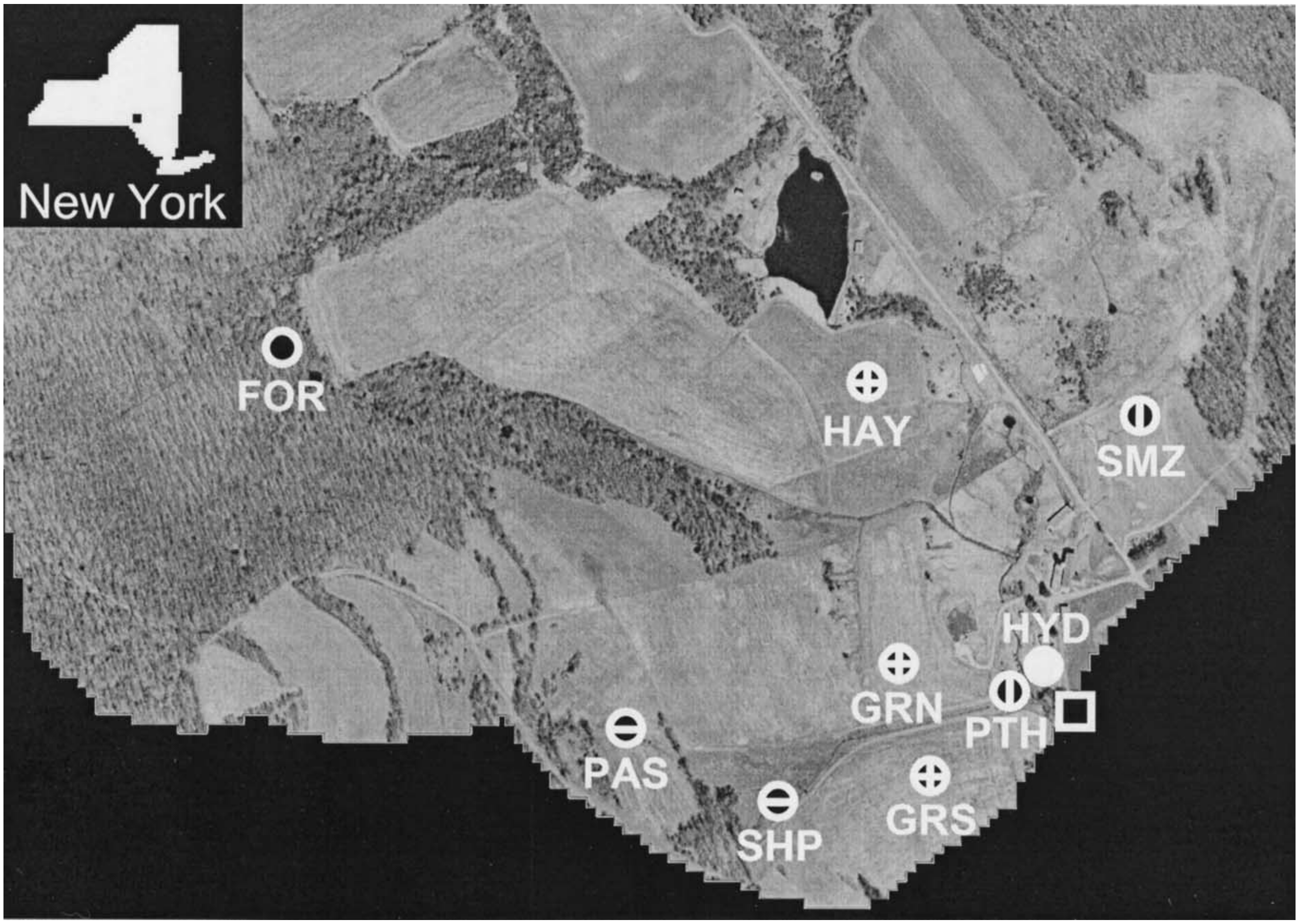

Fig. 1. Location of the nine simulated rainfall application sites within the study watershed. Refer to Table 1 for a description of site codes. Symbols indicate concentrations of soil test phosphorus using Morgan's extraction (1 *M* NaOAc, pH 4.8; Lathwell and Peech, 1965): open circle, 0 to 2 mg kg^{-1}; horizontal hatch, 2 to 5 mg kg^{-1}; vertical hatch, 5 to 10 mg kg^{-1}; cross hatch, 10 to 25 mg kg^{-1}; filled circle, >1000 mg kg^{-1}. The blacked out area indicates the boundary of the watershed above the monitoring station (open square).

ric drop diameter of 1.9 mm, a near-terminal velocity, and a mean kinetic energy 87% of natural rainfall (Humphry et al., 2002). The resulting rainfall intensity (38 mm per 30 min) approximates a 5- to 10-yr storm frequency. A tarp surrounding the system minimized disruption from wind.

After the sites were established, simulated rainfall was initiated and time to first observed overland flow was recorded for each plot (A and B at each sampling site). Once overland flow was observed entering the collection gutter, 5-min flow volumes (mL) for each plot were recorded by weight, for a total of 30-min, after which rainfall ceased. After weighing, overland flow was combined, producing a 30-min flow-weighted composite sample for each plot. Samples (200 mL) were collected every 5 min, from $t = 0$ to 30 min, from the first plot (A or B) to initiate overland flow. To reduce sample processing costs, a 200-mL water sample was collected from the second plot only at $t = 30$ min. Previous National Phosphorus Project rain simulation results indicate that concentrations of P and TSS in overland flow usually stabilize within the first 20 min of rainfall, and the samples collected at $t = 30$ min (A30, B30) are therefore thought to represent equilibrium flow conditions (P. Kleinman, personal communication). Following the first day's data collection, plots were left for 18 to 24 h to drain to field capacity, after which the rain application and data collection protocol was repeated on the second day. Runoff concentration results for the composite and equilibrium flow samples

Table 1. Nine simulated rainfall application sites sampled in the summer of 2001, representing potentially different phosphorus loading source areas within the dairy farm watershed.

Site code	Site name	Site description	Ground cover†	Cover type	Slope
			%		%
HYD	heifer barnyard	heifer barnyard with heavy manure deposits	10	some debris from fed hay	11
PTH	cow path	cow path leading up from heifer stream crossing	50	sparse close-cropped grass	15
GRN	grazing north	intensive rotational grazing, not yet grazed in 2001	100	improved pasture grasses, lush growth	10
GRS	grazing south	intensive rotational grazing, recently grazed	100	improved pasture grasses, lush growth	10
HAY	hayfield	recently cut hayfield (first cut), little regrowth	80	cut stems of hay grasses	10
PAS	pasture	swale area in extensively grazed hillside pasture	100	unimproved pasture grasses and weeds	13
SMZ	spring in maize field	hillside seep area in plowed cornfield	15	tilled soil, some stones	13
SHP	spring in heifer pasture	hillside seep area in heifer pasture	85	nutsedge and swamp grasses	14
FOR	forest	hardwood forest, flow path at base of slope	75	forest floor herbs and fallen leaves	7

† Measured ground cover included vegetation, detrium, and stones.

Table 2. Soil porosity (2- to 6-cm sampling horizon), percent moisture saturation of soil pore space, time to first observed overland flow, and equilibrium flow rate (flow rate after 30 min of overland flow production) for the nine simulated rainfall application sites.

			Day 1			Day 2		
Site code†	Plot	Porosity	Saturation	Time to overland flow	Equilibrium flow rate	Saturation	Time to overland flow	Equilibrium flow rate
		%	%	min	cm per 30 min	%	min	cm per 30 min
HYD	A	89	74	18	3.8	89	8	2.5
	B	89	74	13	2.1	89	6	2.4
PTH	A	54	33	6	2.0	57	5	2.3
	B	54	29	8	2.0	56	5	2.4
GRN	A	65	41	93	1.5	63	21	0.5
	B	65	35	96	2.1	76	21	1.7
GRS	A	65	45	27	1.5	80	8	2.2
	B	65	54	37	1.2	66	7	2.0
HAY	A	61	63	44	1.4	63	12	2.0
	B	61	49	43	1.5	69	13	2.0
PAS	A	59	58	67	–‡	79	23	0.6
	B	59	57	39	0.2	75	21	0.9
SMZ	A	55	73	13	0.7	92	5	1.6
	B	55	46	13	2.2	69	7	2.6
SHP	A	74	97	5	2.1	100	4	2.3
	B	74	99	5	3.1	100	4	2.9
FOR	A	66	93	37	0.7	85	8	1.5
	B	66	73	48	0.6	92	8	1.1

† Refer to Table 1 for site code descriptions.
‡ Flow from the PAS site was not recorded for 30 min on Day 1 due to excessive time to overland flow production.

are presented in Tables 2 through 5, while results presented in the text refer only to composite flow sample data.

Water samples were transported to a nearby laboratory and prepared for analysis. Total phosphorus (TP) samples were acidified and refrigerated, and subsequently processed at the Upstate Freshwater Institute, where molybdate reactive orthophosphate was measured, following acid digestion (USEPA, 1983; ELAP Method #9061; Standard Methods 18: 1500PBS; 0.005 mg L^{-1} detection limit). Total dissolved phosphorus (TDP) samples were filtered (pre-washed 45-μm membrane), acidified, and refrigerated, and were subsequently processed at the Upstate Freshwater Institute, where molybdate reactive orthophosphate was measured, following acid digestion. Particulate phosphorus (PP) was computed as the difference between TP and TDP. Total suspended solids (TSS) were calculated from the weight of solids captured on an oven-dry Whatman (Maidstone, UK) #1 paper filter.

Volumetric moisture contents of plot soils were determined from 44-cm^3 soil cores (2- to 6-cm sampling depth, two to four cores per plot) collected immediately before each simulated rainfall event, and immediately after cessation of rainfall on the second day. Soil moisture content was determined by weight loss on drying (2 d at 60°C). Soil volume was corrected for organic matter content (loss on ignition at 500°C) and for gravel content (volume of gravel removed by a 2-mm sieve using an assumed particle density of 2.41 g cm^{-3} determined by measurement of weight/volume of gravel removed from samples).

Additional soil samples (10 cores per plot, 0- to 15-cm sampling depth, bulked) were collected from each plot at the end of the second day. These samples were dried and sieved (2 mm), and were analyzed for soil test phosphorus (STP) using three methods: (i) Morgan's STP was determined with 1 *M* NaOAc extractant, buffered to pH 4.8 (Lathwell and Peech, 1965); (ii) total STP was determined by modified semimicro Kjeldahl digestion (Bremner, 1996); and (iii) water-soluble STP was measured by shaking 0.5 g of soil in 5 mL of distilled water for 1 h (soil to solution = 1:10), filtering the supernatant through a Whatman #1 paper filter, and determining P colorimetrically (Murphy and Riley, 1962). Soil samples were also processed for organic matter content (loss on ignition at 500°C).

Statistical analysis was performed using the SPLUS-6 statistical package (Insightful Corporation, 2001). Tukey's multiple comparison (Tukey's multicomp routine) was used to test for significant differences among plot means when analysis of variance (aov routine) indicated overall differences among plot means, for either 30-min flow-weighted composite samples or equilibrium flow samples. General linear models (glm routine) were used to predict overland flow P concentrations from STP.

RESULTS AND DISCUSSION

Overland Flow

Time to overland flow following rainfall initiation varied by an order of magnitude among sites (Table 2, Fig. 2). On the first day of rainfall simulation, the four nonfield, nonforest sites (SMZ, SHP, HYD, PTH) exhibited much shorter times to overland flow (5–18 min) than the remaining sites (27–96 min). On the second day of rainfall simulation antecedent soil moisture conditions approximated field capacity at all sites, and time

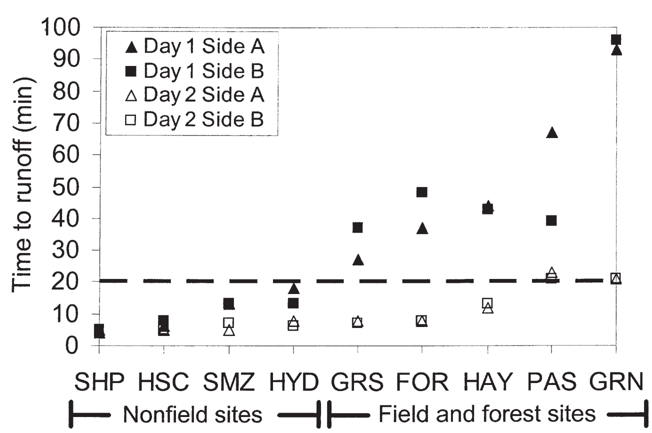

Fig. 2. Time to first observed overland flow under simulated rainfall conditions (38 mm per 30 min application rate). At each site two paired plots (solid triangles and squares) were sampled on two consecutive days (first day: solid triangles and squares; second day: open triangles and squares). Refer to Table 1 for a description of site codes. The dashed line indicates 20-min threshold.

to overland flow generation was correspondingly more uniform, ranging from 4 to 23 min (Table 2). These results support a commonly held viewpoint that overland flow generation from temperate upland soils is largely controlled by mechanisms of saturation excess (Walter et al., 2003), and that soils with higher initial moisture contents are quicker to produce overland flow. In fact, time to runoff was correlated (R^2 = 71%) with unsaturated pore volume (Hively, 2004).

Soil porosity was fairly consistent among the field sites (52–65%), but was significantly higher at SHP (74%) and HYD (89%), where soil organic matter contents were high and bulk densities were low (Table 2). First-day volumetric soil moisture content ranged higher at the SMZ, SHP, HYD, and FOR sites (0.33, 0.64, 0.66, and 0.55 cm^3 H_2O cm^{-3} soil) than at the four field sites (0.25–0.35), and was lowest (0.17) at the compacted heifer pathway (PTH). This corresponded to an average percent saturation of 64, 98, 74, and 83% for the SMZ, SHP, HYD, and FOR and sites, respectively; 38 to 57% for the field sites; and 31% for PTH. On the second day percent saturation of pore space ranged from 56 to 100% (Table 2). The four sites with the shortest times to runoff on Day 1 (SMZ, SHP, HYD, and PTH) showed little difference in time to runoff between Day 1 and Day 2, indicating, perhaps, that they were already near field capacity when the experiment began (SMZ, SHP due to ground water seepage; HYD due to the presence of cows), or had shallow, compacted soils with infiltration excess runoff production (PTH).

Under dry conditions typical of the summer months, sampled agricultural field areas (GRS, HAY) and forested areas (FOR) are not likely to generate overland flow in response to an intense rain event lasting less than 25 min. During the summer, short, intense cloud bursts are likely to generate infiltration excess overland flow from impermeable surfaces such as farm roads, cow paths, and other compacted areas, as typified by the heifer cow path (PTH; overland flow generated within 8 min of rainfall). Additionally, sites that retain high soil moisture throughout the summer, such as spring areas (SMZ, SHP; overland flow generated within 13 min of rainfall), will also generate overland flow during the short, intense precipitation events typical of the dry summer months. Because the heifer barnyard site was sampled on a different date than the remaining sites, it was unclear whether the high initial moisture content and quick overland flow generation observed at this site (HYD; overland flow generated within 18 min of rainfall) was due to urine deposits onto packed manure or to previous rainfall, although the nature of the site seemed to indicate that summertime overland flow generation was likely (Hively, 2004).

On both days, once overland flow was observed, flow rates generally increased for 10 to 25 min at all sites until an equilibrium flow state was achieved. Data from the SHP and HAY sites are provided to illustrate this pattern (Fig. 3). Equilibrium flow rate, defined as the flow rate 30 min after first observed overland flow, ranged from 0.2 to 3.1 cm per 30 min, with most sites falling between 1.1 and 2.2 cm per 30 min (Table 2). The high

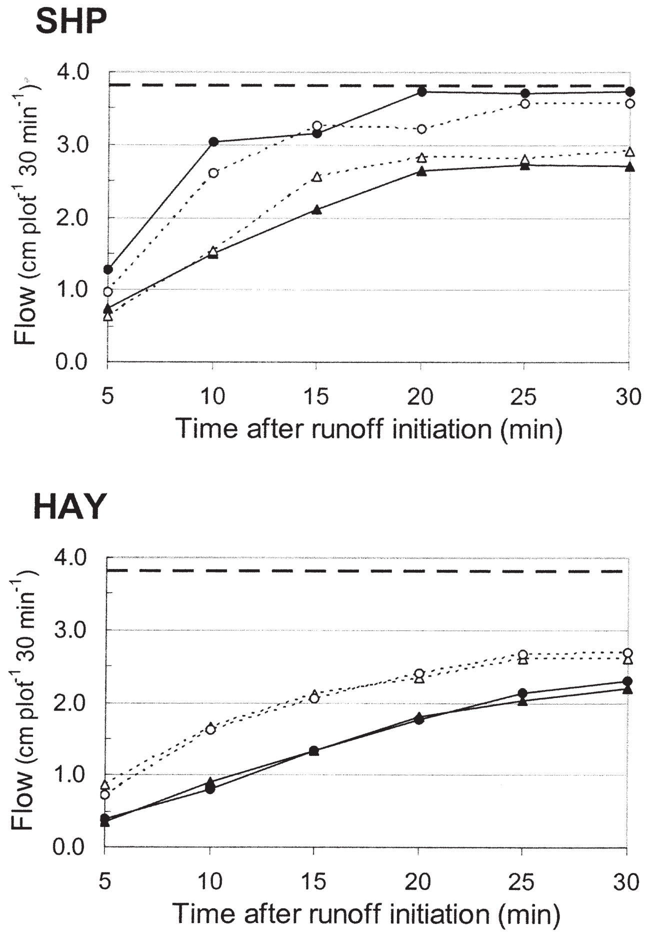

Fig. 3. Flow of surface overland flow from simulated rainfall application plots, including a seep area within an extensively grazed heifer pasture (SHP) and a recently cut hay field (HAY). At each site two paired plots (solid triangles and circles) were sampled on two consecutive days (first day: solid triangles and circles; second day: open triangles and circles). The dashed line indicates rainfall application rate (38 mm per 30 min).

flow rate exhibited by SHP was likely due to a high soil water table, and the low flow rates exhibited by FOR and PAS were likely attributable to high infiltration rates associated with well-structured soils (FOR) and the abundant presence of burrowing earthworms (PAS).

Soil Test Phosphorus

Morgan's STP values (Jokela et al., 1998) generally score in the low range (<2 mg kg^{-1}) for forested, nonmanured areas; in the moderate range (2–4 mg kg^{-1}) for extensively cropped, upper watershed fields; in the optimum to high range (4–20 mg kg^{-1}) for intensively cropped, lower watershed fields; and in the excessively high range (>20 mg kg^{-1}) for barnyards. These values reflect differences in cropping intensity, historical rates of manure application, frequency of cow traffic, and distance from the barn.

A similar pattern of STP was observed among the rainfall simulation sites: the forest (FOR, 1.3 and 1.6 mg kg^{-1} [Plots A and B, respectively]), the extensively grazed pasture (PAS, 2.6 and 3.1 mg kg^{-1}) and the spring area within extensively grazed pasture (SHP, 3.9 and 4.4 mg

Table 3. Soil characteristics, soil test phosphorus (STP), and manure application histories for the nine simulated rainfall application sites.

Site†	Plot	Soil type‡	Restricting layer	pH	Total STP§	Morgan's STP¶	Water-soluble STP#	Manure history
					mg kg^{-1}			
HYD	A	WmC	rock at 0.6 m	7.9	3955	1344.2	389.3	abundant manure from 18 heifers, deposited daily
	B			8.6	3955	2020.5	389.3	
PTH	A	WmC	fragipan at 0.24 m	6.0	724	8.8	4.4	some deposition by 18 heifers during extensive grazing
	B			5.8	626	4.6	3.3	
GRN	A	WmC	rock at 0.24 m	6.6	1118	21.5	4.7	last grazed in summer 2000 (35 cows for 2 mo)
	B			6.8	1123	23.1	5.7	
GRS	A	WmC	fragipan at 0.33 m	6.1	1118	9.7	3.5	recently grazed by 35 cows for 4 wk
	B			6.3	1114	14.8	6.0	
HAY	A	WmC	fragipan at 0.33 m	6.8	1044	16.1	3.7	8.6 kg P ha^{-1} surface-applied manure, fall 2000
	B			7.1	1063	24.3	6.2	
PAS	A	VlC	dense soil at 0.53 m	5.3	826	2.6	1.2	some deposition by 18 heifers during extensive grazing
	B			5.2	909	3.1	1.4	
SMZ	A	OfB	fragipan at 0.24 m	6.3	710	8.3	3.8	8.6 kg P ha^{-1} surface-applied manure, fall 2000
	B			6.4	835	8.6	3.7	
SHP	A	VlC	dense soil at 0.24 m	5.3	835	3.9	1.6	some deposition by 18 heifers during extensive grazing
	B			5.3	882	4.4	1.2	
FOR	A	EkC	dense soil at 0.42 m	4.9	835	1.6	0.6	no manure application
	B			4.9	840	1.3	0.5	

† Refer to Table 1 for site code descriptions.
‡ USDA-NRCS official SSURGO soil series name (silt loams: Ek, Elka; Of, Ontusia; Vl, Vly; Wm, Willowemoc) and slope class (B: 3–8%; C: 8–15%).
§ Soil test phosphorus using a modified semi-micro Kjeldahl extraction (Bremner, 1996).
¶ Soil test phosphorus using Morgan's extraction (Lathwell and Peech, 1965).
# Water-extractable soil test phosphorus, 10:1 water to soil ratio (Murphy and Riley, 1962).

kg^{-1}) exhibited Morgan's STP in the low to moderate range (Table 3), while the recently grazed intensive pasture (GRS, 9.7 and 14.8 mg kg^{-1}), the spring area within a tilled maize field (SMZ, 8.3 and 8.6 mg kg^{-1}), and the compacted heifer cow path (PTH, 4.6 and 8.8 mg kg^{-1}) exhibited STP in the optimum to high range. The hayfield (HAY, 16.1 and 24.3 mg kg^{-1}) and the intensively grazed pasture with long-term history of manure application (GRN, 21.5 and 23.1 mg kg^{-1}) exhibited high to excessively high STP. The heifer barnyard (HYD) exhibited exceptionally high Morgan's STP (1344 and 2020 mg kg^{-1}) due to its substrate, which was a thick pack of manure, well mixed with chaff and soil. Water-soluble STP values were 30 to 80% lower than Morgan's STP, and total STP values were approximately two orders of magnitude higher (Table 3).

Total Dissolved Phosphorus in Overland Flow

Concentrations of TDP in overland flow ranged from low to extremely high among the sampling sites (Table 4). Two sites (SHP, FOR) exhibited average TDP concentrations below 0.02 mg L^{-1}. The fall-manured spring site (SMZ) along with the extensively grazed pasture (PAS) and the cow path (PTH) produced overland flow with moderate concentrations of TDP (0.11, 0.12, and 0.18 mg L^{-1}, respectively), while the three intensively cropped field sites (GRN, HAY, GRS) exhibited moderate to high TDP concentrations (0.39–0.65 mg L^{-1}). The heifer barnyard (HYD) produced extremely high concentrations of TDP in overland flow (11.6 mg L^{-1} average).

History of manure application varied among the plots (Table 3). For the seven sites without recent manure, concentrations of TDP in 30-min composite samples of overland flow were correlated to Morgan's STP (TDP [mg L^{-1}] = 0.0056 + 0.0180 × Morgan's STP [mg kg^{-1}]; adjusted R^2 = 84%, F = 132.3, $p < 0.001$). This result (Fig. 4) is consistent with relationships found for similar soils by Jokela et al. (1998) and Kleinman (1999). Water-soluble STP showed a similar correlation (TDP [mg L^{-1}] = −0.0416 + 0.0724 × water-soluble STP [mg kg^{-1}]; adjusted R^2 = 72%, F = 65.7, $p < 0.001$). Samples of overland flow collected under equilibrium conditions (t = 30 min) also demonstrated correlation between

Table 4. Average concentrations of total suspended solids (TSS), total phosphorus (TP), particulate phosphorus (PP), and total dissolved phosphorus (TDP) in composite (0–30 min) and equilibrium flow (at 30 min) overland flow samples.

Site†	30-min flow composite					Equilibrium flow (t = 30 min)				
	TSS	TP	PP	TDP	% PP‡	TSS	TP	PP	TDP	% PP
	mg L^{-1}				%	mg L^{-1}				%
HYD	375a§	13.16a	1.57a	11.60a	12a	280	13.74	1.87	11.87	13
PTH	540a	0.99b	0.81ab	0.18de	82c	450	0.73	0.57	0.16	79
GRN	23b	0.58cd	0.21c	0.37cd	36b	21	0.54	0.19	0.36	34
GRS	33b	0.95b	0.31c	0.64b	33b	25	0.83	0.22	0.61	26
HAY	35b	0.68bc	0.26c	0.43bc	38b	16	0.67	0.19	0.48	29
PAS	16b	0.25cd	0.13c	0.12e	50bc	22	0.22	0.10	0.11	42
SMZ	615a	0.62bcd	0.51bc	0.11e	82c	560	0.59	0.51	0.08	87
SHP	137b	0.30cd	0.28c	0.020e	93	100	0.24	0.22	0.020	93
FOR	72b	0.19d	0.18c	0.007e	94	54	0.08	0.07	0.007	92

† Refer to Table 1 for site code descriptions.
‡ % PP = 100 × (TP − DP)/(TP) = percent of total P load delivered as particulate P.
§ Letters indicate significantly different treatment means, as determined by Tukey's multiple comparison, α = 5%.

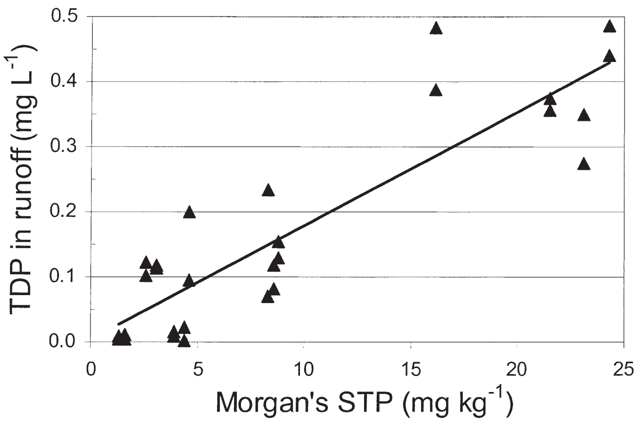

Fig. 4. Concentrations of total dissolved phosphorus (TDP) in 30-min composite overland flow samples versus Morgan's soil test phosphorus (STP) for the seven rainfall simulation sites without fresh manure (TDP [mg L^{-1}] = 0.0056 + 0.018 × STP [mg kg $^{-1}$]; adjusted R^2 = 84%). The line indicates linear fit.

TDP and either Morgan's STP (TDP [mg L^{-1}] = −0.0056 + 0.0191 × Morgan's STP [mg kg^{-1}]; adjusted R^2 = 79%, F = 118.8, $p < 0.001$) or water-soluble STP (TDP [mg L^{-1}] = −0.0493 + 0.0748 × water-soluble STP [mg kg^{-1}]; adjusted R^2 = 67%, F = 50.7, $p < 0.001$).

Concentrations of TDP in overland flow from the seven sites that had not received recent manure deposits showed little variation over the 30 min of sampling, and TDP concentrations were similar on both days of rainfall application. Data from the GRN site are provided as an example (Fig. 5). In contrast, the two sites with fresh manure (GRS, HYD) demonstrated elevated concentrations of TDP during the first 10 min of flow on both days. Data from the GRS site are provided as an example (Fig. 5).

Total Suspended Solids and Particulate Phosphorus in Overland flow

Average composite TSS concentrations were highest at the SMZ (615 mg L^{-1}), PTH (540 mg L^{-1}), and HYD (375 mg L^{-1}) sites (Table 4). Concentrations of TSS from the remaining sites were comparatively low, ranging from 16 to 137 mg L^{-1}. As was expected, the lowest TSS concentrations were observed in overland flow from plots with high ground cover (Table 1). All sites, on both days, exhibited initially elevated TSS concentrations during the first 10 min of overland flow. Data from the PTH and HAY sites are provided as an example (Fig. 6). The TSS concentrations were generally similar on both consecutive days of rainfall simulation.

Particulate phosphorus (PP = TP − TDP) ranged from 0.13 mg L^{-1} (PAS) to 1.57 mg L^{-1} (HYD) among the sites (Table 4). Particulate P made up a large percentage (93, 94%) of the TP load on the sites with lowest TP concentrations (SHP, FOR). Sites with high sediment delivery rates and moderate TDP (SMZ, PTH) delivered 82% of TP as PP. The HYD site, with high TSS and excessively high TDP, delivered only 12% of TP as PP, while the remaining field sites ranged from 33 to 50%.

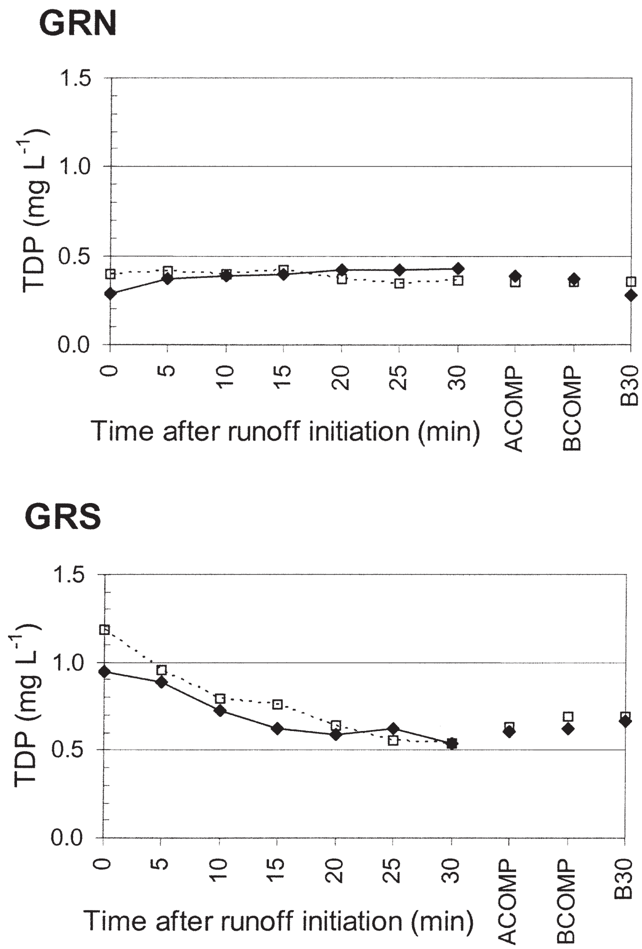

Fig. 5. Concentrations of total dissolved phosphorus (TDP) in overland flow from intensively managed pasture (regrowth, GRN; recently grazed, GRS) on the first (diamonds) and second (squares) days of rainfall simulation. Samples were collected in 5-min increments from the first paired plot to produce overland flow; 30-min composite samples (ACOMP, BCOMP) and equilibrium flow samples (A30, B30) were collected from both plots.

Site by Site Comparison and Analysis

Three sites (GRN, HAY, and GRS) were representative of mid-slope soils that are comparatively productive, have a history of manure and lime application, and are subject to intensive agricultural management. Accordingly, STP values at these sites were comparatively high (9.7–24.3 mg kg^{-1} Morgan's STP), reflecting the history of manure application. Concentrations of TDP in overland flow (0.37–0.64 mg L^{-1}) were also high, exceeded only by the concentrations observed at the heifer barnyard site. A comparison of recently grazed pasture (GRS) and pasture regrowth (GRN) showed the effect of intensive grazing on P concentrations in overland flow. Both sites had similar ground cover (100%) and vegetation (improved pasture grasses), but GRS had been recently grazed (35 cows ha^{-1} for 4 wk), and several-day-old manure was present on 2.8% of Plot A and 0.8% of Plot B. The GRN site, in contrast, had not yet been grazed in 2001. Although Morgan's STP was lower at GRS (9.7 and 14.8 mg kg^{-1}), the GRS site yielded higher TDP concentrations in overland flow (0.64 mg

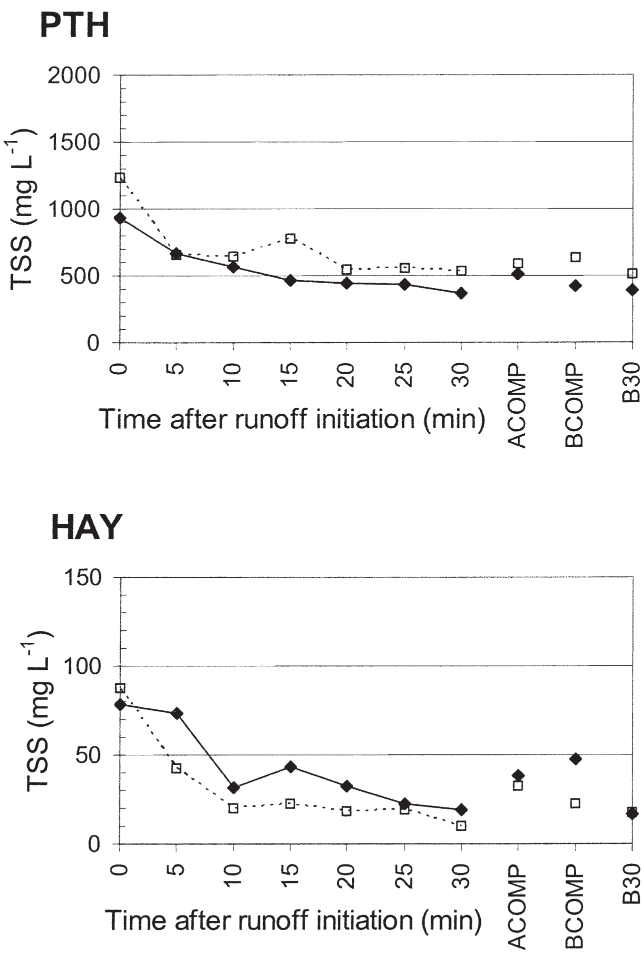

Fig. 6. Concentrations of total suspended solids (TSS) in overland flow from a heifer cow path (PTH) and a recently cut hay field (HAY) on the first (diamonds) and second (squares) days of rainfall simulation. Samples were collected in 5-min increments from the first paired plot to produce overland flow; 30-min composite samples (ACOMP, BCOMP) and equilibrium flow samples (A30, B30) were collected from both plots.

L^{-1}) than did GRN (0.37 mg L^{-1}) or any other field site. Further research into the effect of grazing on TDP concentrations in overland flow may be warranted.

The PAS site, located in an extensively grazed, upper-hillside pasture, was not a significant source of TSS (16 mg L^{-1}), and was only a moderate source of TDP (0.12 mg L^{-1}). Manure deposition from extensive grazing had evidently not led to substantial accumulation of STP (2.6–3.1 mg kg^{-1}). The high infiltration rate exhibited by the PAS site was attributed to a loose soil structure and evident earthworm activity.

The SMZ site, located in an area of concentrated flow from a hillside spring, was not representative of the surrounding cornfield, in that maize had failed to establish in the seep area and it was apparent that considerable springtime overland flow had occurred. Although fall manure application and tillage were uniform across the field, overland flow during the winter and spring had evidently leached available soil P from the SMZ sampling area. Soil tests revealed Morgan's STP of 8 mg kg^{-1} at the SMZ site, 16 mg kg^{-1} in the flow path leading away from the site, and 23 mg kg^{-1} in each of three transects taken within the surrounding cornfield (Hively, 2004). Concentrations of TDP in overland flow (0.11 mg L^{-1}) were correspondingly lower than might be expected from the cornfield as a whole. Observed concentrations of TSS (615 mg L^{-1}) in flow from the SMZ site were high, indicating that the exposed, plowed soil remained susceptible to erosion. Results from the SMZ rainfall simulation site suggest that flow from hydrologically active areas within plowed, manured fields may leach P from the soil in the winter and spring months, leading to reduced concentrations of TDP in overland flow from the seep areas in the summer and early fall.

The SHP site, located in a hillside spring area, was rutted with hoof prints from grazing heifers and, although the heifer grazing was not intensive, some manure was likely deposited in the area. The observed overland flow concentration of TDP was quite low (0.02 mg L^{-1}), indicating that the extensively grazed hillside hydrologic source area was not a significant source of P. Leaching of available P by springtime overland flow at the SHP site is perhaps indicated by a comparison with the extensively grazed pasture site (PAS), where higher concentrations of TDP in overland flow were observed (0.11 mg L^{-1}), despite lower associated values for Morgan's STP (2.6, 3.1 mg kg^{-1}). However, because the STP values observed at the SHP sampling site (3.9–4.4 mg kg^{-1}) were similar to the STP of soil samples collected in the surrounding area (3.1 mg kg^{-1}), the low observed concentrations of TDP in overland flow may simply be the result of minimal manure deposition in the area.

The HYD site, located in a barnyard area frequented by standing heifers, was clearly a concentrated source area for P. Soil test P at this location was extremely high (1344 and 2020 mg kg^{-1} Morgan's STP) due to abundant manure deposition. Observed TDP concentrations (11.6 mg L^{-1}) were an order of magnitude greater than TDP concentrations observed at any other rainfall simulation site. Concentrations of TSS (375 mg L^{-1}) were also high, most likely due to the low ground cover (10%), and eroded sediment was substantially enriched in P.

The PTH site, located on a compacted cow path leading up from a stream crossing, produced moderate concentrations of TDP in overland flow (0.18 mg L^{-1} TDP). On the first day of simulated rainfall the PTH site produced 0.20 to 0.25 mg L^{-1} TDP during equilibrium flow, whereas on the second day it produced only 0.1 mg L^{-1} TDP. Evidently there was a washout effect on the first day, as rainfall effectively removed available P from the cow path surface. Soil test P (4.6 and 8.8 mg kg^{-1} Morgan's STP) was lower than might have been expected from the frequent cow traffic. Perhaps little manure is deposited at this location because the steepness of the path prevents the cows from idling. Erosion from the PTH site was quite high (540 mg L^{-1} TSS), due to the steep slope (15%), minimal ground cover (50%), and frequent traffic. The cow path exhibited an elevated loss of sediment during the first 10 min of flow (Fig. 6). This result might be expected, given the impermeable nature of the PTH site and the fact that its soil surface is likely to be loosened by moving cows.

Table 5. Loads of total suspended solids (TSS), total phosphorus (TP), total dissolved phosphorus (TDP), and particulate phosphorus (PP) delivered in overland flow from the nine rainfall simulation sites, during a 25-min simulated rainfall event on the first day of rainfall application, under dry summer conditions.

Site†	TSS	TP	TDP	PP
	mg plot^{-1}‡			
HYD	3 730	110	112	0
PTH	12 675	29	7	22
GRN	0	0	0	0
GRS	0	0	0	0
HAY	0	0	0	0
PAS	0	0	0	0
SMZ	3 282	3	0	2
SHP	4 550	10	1	9
FOR	0	0	0	0

† Refer to Table 1 for site code descriptions.
‡ Plot area was 1.95 m^2.

The forested site (FOR) had no history of manure application and exhibited low STP (1.3–1.6 mg kg^{-1}). Concentrations of TDP in overland flow from the forested site were also low (0.005–0.011 mg L^{-1}, 0.007 mg L^{-1} average), supporting the hypothesis that clean water from the forested landscape will dilute higher P concentrations from other landscape areas. Maintenance of forested land is therefore an important positive factor in whole-farm management of water quality. Similar TDP concentrations were observed during extensive streamwater monitoring at a nearby nonfarm watershed (0.011 mg L^{-1} average; Bishop et al., 2003).

Total sediment and P loads delivered during the first 25 min of simulated rainfall on the first day (dry conditions) on are shown in Table 5. Since overland flow did not occur within 25 min at any of the field locations, resultant load values are zero; all loads originated from nonfield areas. Of the nonfield areas, the seep areas yielded sediment, but P loads were minimal, probably because P had been leached during springtime runoff production. During short, intense summer rainfall events, most P loading appears to originate with flow generated from impervious areas receiving manure, such as the barnyard and cow path sampling sites.

Implications for Management and Watershed Modeling

Average concentrations of TDP and PP observed at a stream water monitoring station located at the outlet of the farm watershed (Bishop et al., 2003) are three to four times higher during summer periods than during the winter and springtime. Results of simulated rainfall application suggest that P loading during high-intensity, short-duration summer storms may originate primarily from hydrologically active nonfield areas, many of which are also high-P source areas. Of the nine sites evaluated by this experiment, the four nonfield, nonforest locations were the quickest to produce overland flow under dry summer conditions, and exhibited the highest concentrations of suspended solids (TSS). Two of the nonfield sites (barnyard, cow path) also exhibited the highest observed concentrations of dissolved phosphorus (TDP) and particulate phosphorus (PP), indicating that they are critical areas for P loading. Upper-watershed areas (forest, extensive pasture), in contrast, exhibited low to moderate TDP concentrations (0.007–0.12 mg L^{-1}) and low soil test P (1.3–3.1 mg kg^{-1} Morgan's STP). Forested areas in the upper watershed may play an important role in maintaining stream water quality by diluting flow from high-P manured source areas.

Intensively managed fields in the lower watershed exhibited elevated (0.18–0.64 mg L^{-1}) TDP concentrations. These areas represent soils that have accumulated P (8.3–24.3 mg kg^{-1} Morgan's STP) as a result of long-term manure application. The high source potential indicates the importance of field-based P management strategies that avoid manure spreading in hydrologically active areas. Frequently saturated spring areas within agricultural fields exhibited low to moderate Morgan's STP (3.9–8.6 mg kg^{-1}) and lower than expected concentrations of TDP in overland flow (0.02–0.11 mg L^{-1}), indicating a substantial loss of P inputs before the dry summer period. Elevated concentrations of TDP (0.64 mg L^{-1}) were observed in runoff from a recently grazed pasture, in comparison with pasture regrowth (0.37 mg L^{-1}), indicating a temporal effect of intensive grazing on P loss.

Rainfall simulation can provide estimates of P concentrations in overland flow from various landscape components, for use in hydrological modeling of P transport. Although this study focused on one farm and sites were not replicated within each land use type, the results were intuitively consistent with observations made on other farms within the New York City watershed and similar implications might be drawn for farms throughout the U.S. Northeast, wherever sloping watersheds and shallow soils promote variable source area hydrology as a dominant P loading process. The P concentrations observed in this study are likely to vary temporally and spatially, and should not be extrapolated to geomorphic settings other than temperate upland watersheds in the Catskills region of New York. Nonfield areas, however, are an important component of all agricultural landscapes, and their hydrological and P-loading potential should be explicitly considered in any model of watershed nutrient transport. Results of this study concur with the program of Whole Farm Planning and best management practice implementation that is promoted in the New York City watershed: minimize overland flow from barnyard areas, avoid spreading manure on hydrologically active areas, implement agronomic techniques for erosion control, and maintain forested areas within the landscape.

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